Review Paper: Comparison of the Fit, Accuracy, and Fracture Resistance of 3D-Printed Versus Milled Zirconia Single Dental Crowns: A Systematic Review

Maryam Jahangiri[1*], Hedie Derakhshi[2], Sayed Shojaedin Shayegh[1]

1. Department of Prosthodontics, Faculty of Dentistry, Shahed University, Tehran, Iran
2. Department of Prosthodontics, Faculty of Dentistry, Babol University, Babol, Iran

Use your device to scan and read the article online

Citation Jahangiri M, Derakhshi H, Shayegh SSh. Comparison of the Fit, Accuracy, and Fracture Resistance of 3D-Printed Versus Milled Zirconia Single Dental Crowns: A Systematic Review. Journal of Dentomaxillofacial Radiology, Pathology and Surgery. 2025; 13(3): 1-11.

http://dx.doi.org/10.32592/3dj.13.3.1

Article info:
Received: 15 Oct 2024
Accepted: 09 Dec 2024
Available Online: 20 Dec 2024

Keywords:
*Dental materials
*Monolithic zirconia crowns
*Three-dimensional printing

ABSTRACT

Zirconium oxide has the best mechanical properties compared to other ceramic materials. Modern techniques such as subtractive manufacturing(milling) have acceptable accuracy for restorations. Additive manufacturing (3D printing) has been introduced recently. This new technique has some advantages such as the ability to process complex shapes, optimal use and lower waste of materials. However, the fitness and accuracy of additive manufacturing vs subtractive manufacturing is unclear. The present study aimed to review the accuracy, restorations fit and fracture resistance of printed vs milled zirconia restorations. This systematic review protocol based on PRISMA guidelines. We searched the following databases from 2010 to 2024: Pubmed, Google Scholar, Scopus, Science Direct, Web of Science and Cochrane Library. The inclusion criteria were the Comparative studies that compared milled and 3D printing crowns, studies that clearly reported how restoration fitness was measured, studies that clearly mention the technology and materials. Published works that included veneers, temporary crowns and implant crowns or not mentioned the technology and materials, were excluded. Among 46 related studies, 14 studies most related to our review selected. Three article indicate higher accuracy in printed crowns. however, others show comparable or higher accuracy in milled crowns. Additive manufacturing (AM) has higher internal adaptation. Inaccuracy in horizontal surface of AM is due to layering production. While, 3D printing has best accuracy in vertical surface. Most articles represented that subtractive manufacturing has higher marginal fitness. However, both AM (Additive manufacturing) and SM (subtractive manufacturing) are within acceptable range. Additive manufacturing has acceptable fatigue resistance.

**** Corresponding Authors:***
Maryam Jahangiri.
Address: *Department of Prosthodontics, Faculty of Dentistry, Shahed University, Tehran, Iran*
Tel: *+989394580534*
E-mail: *shayeghshahed2024@gmail.com*

1. Introduction

Among all-ceramic dental restorations, zirconium dioxide (ZrO_2) exhibits the best mechanical properties (1-4). It is renowned for its high toughness, superior mechanical strength, and aesthetic qualities, making it a desirable choice in dentistry (2). However, clinical failures have been reported for zirconia restorations, primarily due to chipping of the veneered ceramic layer on the zirconia framework. While fractures in zirconia frameworks are rare, veneer failures are more common (5, 6).

One approach to mitigate this issue is by creating monolithic zirconia crowns without a separate porcelain layer. Monolithic zirconia restorations offer the advantage of reduced material thickness in contrast to layered or other monolithic ceramics as silicate ceramics (7, 8).

Subtractive technology, mainly through computer-aided design and manufacturing (milling methods), is commonly used to fabricate zirconia restorations. However, this method results in significant waste of prefabricated blocks and may lead to microscopic cracks in the restoration (9). To overcome these concerns, milling the material in its green stage before sintering can help reduce waste and minimize flaws (10-12).

Although milling is energy-intensive and generates noise and heat, new techniques like 3D printing are promising (13, 14). 3D printing allows for processing complex shapes efficiently, optimal material usage, and eliminates the need for cutting tools (15).

According to the EN ISO 900 terminology standard by ASTM (American Society for Testing and Materials), 3D printing refers to joining materials layer by layer from 3D model data to build objects (16).

3D printing has been utilized for creating resin or metal restorations (17-20), metal denture frameworks (21-24), and metal implants (25). While plastic and metal printing have long been utilized in industry, the accuracy of ceramic printing remains underexplored. Ceramic stereolithography has gained prominence in ceramic research and 3D printing in recent years, with advancements in equipment and market growth. 3D printing provides advantages such as unrestricted geometric design for ceramic structures and material savings, rendering it a suitable production method. 3D printing has some advantages due to its ease of adjustments and cost-effectiveness compared to traditional methods. This technology reduces material wastage and costs (26). Research on 3D printing for zirconia veneers is limited.

According to ISO 5725-1, accuracy consists of trueness (proximity of the mean of measurement results to the true value) and precision (repeatability or reproducibility of the measurement) (27).Restoration fit significantly impacts long-term clinical success, with accuracy being crucial and dependent on the manufacturing process (28, 29). Poor marginal fit can result in issues like plaque accumulation, micro leakage risk, and gingivitis (30, 31). Precision in restoration reduces alignment needs, saves clinical time (28), minimizes finishing steps, prevents restoration damage, and enhances quality (32-35). Crowns' brittleness is a prominent issue. It starts from an edge chipping to the entire broke up under occlusal loading. So, fracture resistance of the crowns is an essential part of crowns' features (36). This review aims to assess the accuracy, fitness and fracture resistance of zirconia restorations produced via 3D printing compared to those from milling methods, hypothesizing similar fit, accuracy levels and fracture resistance between the two methods.

2. Materials and Methods

This systematic review was conducted by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement and the PICO(S) approach (patient or population, intervention, control or comparison, outcome, and study types). The PICO question was formulated: In single tooth-supported zirconia crowns (P), does printer technology (I) provides similar marginal fit, accuracy and fracture resistance, (O) compared to milling method fabrication (C)?

The search strategy included conducting an electronic search through Embase, Scopus, Web of Science, the Cochrane Library databases, Google Scholar and PubMed to find suitable articles. References from database searches were exported into a systematic review platform for removing duplicate articles (Rayyan intelligent systematic review; Rayyan systems Inc). A team of two reviewers screened the articles. Reviewers had a good knowledge of the topic and worked independently. For reducing the risk of selection errors and bias, a prosthodontist supervised the screening procedures.

The search inclusion criteria were: studies published between January 1, 2010, and June 30, 2024, and limited to studies published in English, which included all or part of the keywords in their title or abstract, and comparative articles that evaluate fitness and accuracy of zirconia crowns made by printer and milling technology. Systematic reviews and non-English articles were excluded from the search. Also, the references of the selected articles were checked manually for the existence of articles according to the inclusion criteria.

A list of keywords was used as follows:

monolithic zirconia crowns; 3D printing; milling; accuracy; clinical precision; fracture resistance; dental materials; mechanical behavior of materials; three-dimensional printing.

Exclusion criteria included studies on temporary crowns and bridges, as well as studies that did not answer the PICO question (Table 1).

Table 1. Exclusion and Inclusion criteria

Inclusion criteria	Exclusion criteria
Studies in English Comparative studies Studies that answered the PICO question Studies that clearly reported how restoration fitness was measured Studies that clearly mention the brand of technology and materials used	Studies that were not relevant to the PICO question Case report studies Animal studies Expert opinions Studies that did not clearly report how restoration fitness was measured Studies that did not clearly mention the brand of technology and materials used

3. Results

After reviewing 746 articles that had titles related to keywords, the abstracts of 82 articles studied, articles that were done on temporary crowns, bridges, laminates, veneers, endo crowns, inlays and inlays, and materials other than zirconia, case report articles, and the articles that were not related to the PICO question excluded from the study. The full text of 24 laboratory articles (37-61) by the entry criteria studied. One study was excluded from the review due to a lack of detailed reporting of the printing technology used (37). eight study was excluded from the review due to concentrate in other subjects (45, 46, 50, 51, 54, 56-58).The excluded articles and reasons are summarized in Table 2. The Inclusion studies are summarized in Table 3. (Figure 1)

Table 2. Excluded study with their reason

Study	Reason
Cameron et al (47)	This study concentrated in printing orientations
Aggag et al (46)	This study concentrated in milled crown in stone cast vs printed cast
Hsu et al (37)	a lack of detailed reporting of the printing technology used
Kang et al (52)	This study concentrated in printed or milled provisional restorations.
Thomas et al (51)	This study concentrated in printed or milled interim restorations
Ioannidis et al (57)	This study concentrated in occlusal veneers.
Rues et al (55)	This study concentrated in maxillary central incisor veneers.
Lim et al (58)	This study concentrated in occlusal inlays.
Abad-Coronel et al (59)	This study concentrated in printed or milled provisional restorations.

Table 3. Articles' results in a glance

Subject	Results In A Glance	Studies	Year	Results
adaptation	3D Printed crowns had higher marginal adaptation than milling ones.	Abualsaud et al (42)	2022	The restoration accuracy and Trueness (axial, internal and occlusal) restoration in the 3D print group was better than the milling methods group.
		Marouki et al (45)	2023	The crowns of both techniques had acceptable marginal and internal fit. Self-glaze zirconia crowns had higher accuracy in internal fitness.
		Zhu et al (60)	2023	3D printed zirconia crowns were comparable with milled ones in marginal fitness and had better fitness in intaglio surface.
		Li,b et al (44)	2021	Trueness, marginal, occlusal and axial fitness were not significantly different between the two groups. however, SLA crowns had higher trueness than milled group

		Li et al (38)	2023	Printed crowns with knife edge finish line were associated with higher defects.
		Refaie et al (41)	2023	The results of the milled crowns were better, however, the printed restorations had acceptable results in terms of marginal fit and internal fit.
		Lerner et al (43)	2021	The trueness of the restoration in the 3D printing group was worse than that of the milling group. Nevertheless, the accuracy of the printed group was clinically acceptable.
	Milling methods had higher marginal adaptation than 3D Printed crowns.	Wang et al (39)	2021	Marginal fitness (except in the axial region) and internal fitness of the milling methods group are better. The dimensional accuracy obtained for both materials was within the clinically acceptable range
		Revilla-León (49)	2020	Additive crowns had more marginal and internal fitness than milling methods group.
		Wang et a l (40)	2019	Trueness of the 3D printing group restorations was not worse than milling group.
		Camargo et al(56)	2022	Adaptation is related to cement space. Laboratory milling crowns have best adaptation. however, chairside milling and printed crowns are within acceptable range.
		Kalman et al (48)	2024	This in vitro study suggests 3D-printed zirconia for crowns and veneers are within clinical acceptable range
Fracture resistance	3D Printed crowns fracture resistance were equal to milling ones	Kim et al (53)	2022	There is no significant differences between two groups
	3D Printed crowns had higher fracture resistance than milling methods.	Refaie et al (54)	2024	Printed crowns have better fracture resistance
		Li et al (61)	2019	Printed crowns had acceptable strength.

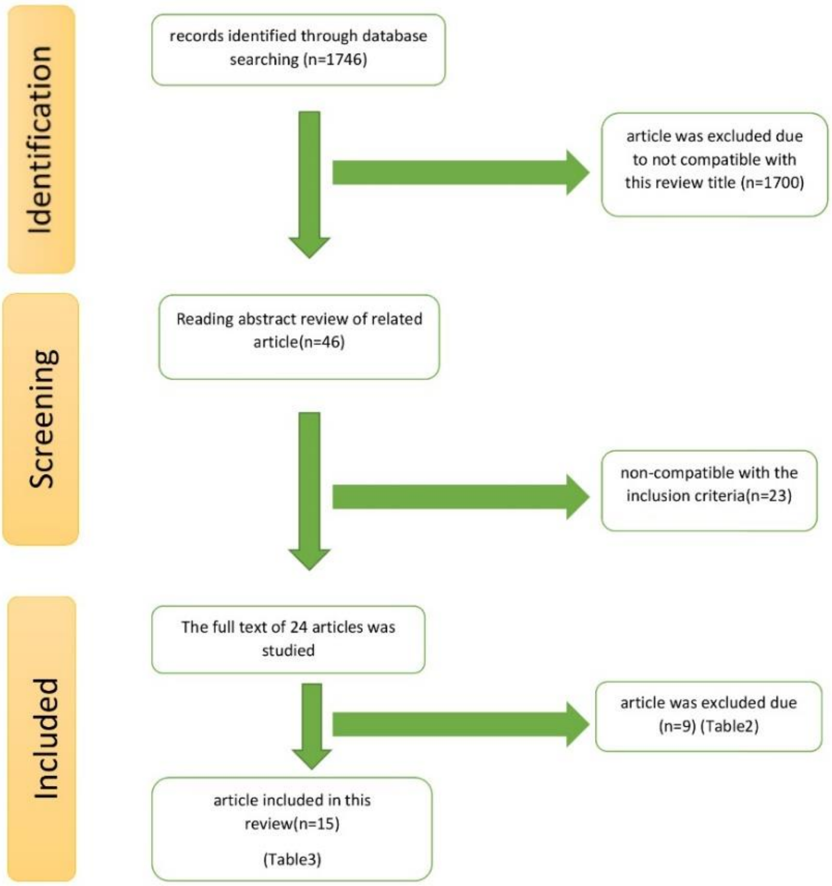

Figure 1. study's data collection strategy

Ten studies measured marginal adaptation using replica and silicone light body techniques or micro-CT(38-45, 49, 50, 60). Three other studies (53, 54, 61) measured the fracture resistance and one study assessed crowns Quality (48) (Table 4).

For Quality assessment, risk of bias tools (RoB 2 cochrane) was used. The RoB 2 is a tool for quality assessment of all entry articles. The study was at low risk of bias according to ROB2 (Table 5).

Table 4. Articles' methods and materials

Authors	year	Study type	The investigated parameter	Sample size	position	measurement methods	subtractive methods	additive method
Abualsaud et al(42)	2022	In-vitro	Trueness , accuracy and fitness	20	Mandibular molar	Micro CT	5-axis milling machine (PrograMill PM7, Ivoclar Vivadent, Schaan, Liechtenstein)	SLA printers (CERAMAKER C900 Flex, 3DCeram Sinto, France)
Kim et al (53)	2022	In-vitro	Fracture resistance	30	Maxillary premolar	universal testing machine (Zwick Zmart-Pro, ZwickRoell GmbH & Co. KG, Ulm, Germany)	Milling machine (DGSHAPE DWX-520 milling machine, Roland Company, Willich, Germany)	CeraFab7500 printer)(
Camergo et al(54)	2022	In-vitro	fitness	30	maxillary molar	micro-CT	LX-O 5-axis & Chairside milling (Dentsply Sirona)	inkjet Carmel 1400 (Xjet) printer
Zhu et al(60)	2023	In-vitro	Accuracy and marginal fitness	30	mandibular first molar	optical microscope	UPCERA milling + VITA (milling)	NPJ (nanoparticle jetting)printer
Kalman et al(48)	2024	In-vitro	Quality assesment	24	Maxillary central incisor crowns + Maxillary lateral incisor veneers	a precementation checklist+ Digital macrophotography	-	CeraFab 7500 system with a layer thickness of 25 µm
Refaie (54)	2023	In-vitro	fracture resistance + internal fit	20	Maxillary premolar	silicone replica technique (SRT) + vertical marginal gap technique	milling machine (DGSHAPE DWX-520 milling machine, Roland company, Willich, Germany)	SLA
Lerner et al (43)	2021	In-vitro	Trueness and accuracy of	20	Maxillary premolar	Micro-CT	5-axis milling machine (DWX-52D®, DGShape)	(LCM) printer (CerafabS65®)
Li et al (44)	2023	In-vitro	Trueness and adaptation	20	maxillary molar	silicone replica technique (SRT)	5 axis miiled machine	SLA
Marouki et al (45)	2023	In-vitro	adaptation and accuracy	20	maxillary premolar	silicone replica technique (SRT) + direct-view technique	milling machine (vhf K5; vhf Camfacture AG)	(self-glazed zirconia; ErranTech Co Ltd)
Refaie et al (41)	2023	In-vitro	Marginal gap and internal fit	20	Maxillary premolar	silicone replica technique (SRT)+ VMGT	milling machine (DGSHAPE DWX-520)	CeraFab7500 printer
Wang et al (39)	2021	In-vitro	Dimensional accuracy and clinical adaptation	30	Maxillary molar	Micro-CT + silicone replica technique (SRT)	CAD–CAM system, X-MILL500 (XM) zirconia	stereolithography systems, CeraFab7500 (CF) alumina and CSL150

			of zirconia crown					(CL) zirconia
Weina Wang et al (40)	2019	In-vitro	Trueness and accuracy	20	maxillary second molar	Micro-CT	5-axis, 2-bur milling DWX-50; Roland DG Corp machine	SLA printer (CERAMAKER 900; 3DCeram Co)
Li et al (61)	2019	In-vitro	Strength and adaptation and density	22	maxillary first molar	Silicone Replica Technique (SRT) + Densitometer + Universal testing machine	-	SLA(CSL150,porimy)
Li et al(38)	2021	In-vitro	Accuracy with different finish line designs	30	maxillary first molar	Micro-CT	milling machine (AK-D4, Aidite, China)	SLA 3D printer (CSL 100, Porimy, China)
Revilla-León et al (49)	2021	In-vitro	Marginal and internal discrepancy	20	Maxillary first premolar	Silicone Replica Technique (SRT)	Milling 5 axis	SLA CERAMAKER 900

Table 5. *Results of bias risk assessment* with risk of bias tools (RoB 2.0 tools)

studies	*risk by Domain*					*Risk of bias*
	abstract	*Introduction*	*methods*	*result*	*discussion*	
Abualsaud et al(42)	yes	yes	yes	yes	yes	Low risk
Marouki et al (45)	yes	yes	yes	yes	yes	Low risk
Zhu et al(60)	yes	yes	yes	yes	yes	Low risk
Li,b et al (44)	yes	yes	yes	yes	yes	Low risk
Li et al (38)	yes	yes	yes	yes	yes	Low risk
Refaie et al(41)	yes	yes	yes	yes	yes	Low risk
Lerner et al (43)	yes	yes	yes	yes	yes	Low risk
Wang et al (39)	yes	yes	yes	yes	yes	Low risk
Revilla-León (48)	yes	yes	yes	yes	yes	Low risk
Wang et al (39)	yes	yes	yes	yes	yes	Low risk
Camargo et al (56)	yes	yes	yes	yes	yes	Low risk
Kalman et al (48)	yes	yes	yes	yes	yes	Low risk
Kim et al (53)	yes	yes	yes	yes	yes	Low risk
Refaie et al (54)	yes	yes	yes	yes	yes	Low risk
Li et al (61)	yes	yes	yes	yes	yes	Low risk

4. Discussion

Based on the findings in the reviewed articles, crowns produced by printing or milling technologies evaluated in two categories: marginal fitness and accuracy, fracture resistance

Printed crowns exhibit lower marginal fitness compared to milling technology. However, almost all studies suggest that this discrepancy falls within an acceptable clinical range (Table 6).

Multiple studies have compared the marginal and internal fitness of milled and 3D-printed zirconia crowns. Wang et al. (39) found superior marginal and internal fit (except axially) with milled crowns compared to SLA-printed crowns. Li et al. (44) reported comparable accuracy between SLA and conventional milling methods, with both techniques being susceptible to margin chipping at knife-edge finish lines due to milling limitations.

Refaie et al. (41) observed larger marginal gaps in printed crowns (80 µm) compared to milled crowns (60 µm), although both were within clinically acceptable limits. Revilla-León et al. (49) found significant differences in both marginal and internal discrepancies between milled and printed crowns, with printed crowns exhibiting more discrepancies. This was attributed to the layer-by-layer nature of 3D printing, which can lead to inaccuracies, especially in curved areas.

Table 6. Marginal fitness compared to CAD-CAM technology in articles

Studies	Milling Marginal Gap	Printed Marginal Gap	Acceptable Range	Results
Abualsaud et al(42)	36.68 ± 6.04 μm	38.26 ± 4.87 μm	50–120 μm	Both within acceptable range
Marouki et al (45)	41.9 μm	51.4 μm	-	Both within acceptable range
Li,b et al (46)	36± 22.6 μm	42.6±9.8 μm	-	Printed and milling technique are comparable.
Li et al (38)	Chamfer= 20.82 ± 4.47 μm Rounded shoulder= 20.42 ± 4.10 μm Knife edge= 23.06 μm	Chamfer= 19.22 ± 0.91 μm Rounded shoulder= 26.20 ± 2.04 μm Knife edge= 25.92 μm	-	Printed and milling technique are comparable.
Refaie et al (41)	60 ± 20 μm	80 ± 30 μm	Lesser than 110 μm	Both within acceptable range
Lerner et al (43)	12.4 μm	25.6 μm	Acceptable=50–120 μm Ideal=lesser than 25 μm	Theres is no significant difference in marginal fitness between two groups.
Wang et al(39)	62 ±9 μm	SLA1= 93 ±32 μm SLA2= 109 ±27 μm	less than 120 μm	Within acceptable range
Revilla-León(49)	37.5 ±50 μm	AM=146.0 ±103.2 μm	17 to 118 μm	Milled group had best marginal fitness. Printed splinted group was in acceptable range. However, anatomic full contour printed group had unacceptable marginal fitness.
Wang et al (40)	35 ±7 μm	34 ±5 μm	-	Printed group was not worse than milling group.

Revilla-León et al. (49) found significant differences in both marginal and internal discrepancies between milled and printed crowns, with printed crowns exhibiting more discrepancies. This was attributed to the layer-by-layer nature of 3D printing, which can lead to inaccuracies, especially in curved areas (40). The primary reason for the superior precision of milling over 3D printing lies in the fundamental process differences. 3D printing, specifically SLA technology, creates a stepped surface, which can compromise dimensional accuracy, especially on curved surfaces (62). This is particularly evident in occlusal or large curved areas, where errors are more pronounced compared to vertical surfaces (63, 64). Consequently, restorations with larger grooves and angles may be more susceptible to inaccuracies (21). Proper curing shrinkage compensation is essential to mitigate these deviations and maintain accuracy (65).

In 2023, Zhu's study (60) revealed comparable marginal quality between printed and milled zirconia crowns. However, 3D printers demonstrated superior trueness in axial and intaglio surfaces. This aligns with the previously discussed limitations of 3D printing, where the step effect is less pronounced in vertical surfaces. The study suggests that the majority of the fit is derived from the axial region, making the printed crowns comparable to milled ones in terms of overall fit.

Carmgo et al. (56) highlighted the strong correlation between crown fitness and marginal accuracy. Marginal mismatches can significantly compromise the adaptation of both the occlusal third and axial regions. Additionally, the amount of cement space plays a crucial role in overall crown fit. Based on these findings, laboratory-milled crowns demonstrated the best adaptation, while chairside-milled and printed crowns fell within acceptable limits.

Kalman's 2024 study (48) compared the quality of printed and milled zirconia anterior crowns and veneers. Both methods were deemed acceptable, with printed crowns exhibiting superior axial fit and retention compared to milled crowns. This increased axial fit is likely the primary factor contributing to the improved adaptation of printed crowns.

Here, some studies suggest that printed crowns are more accurate than milled ones. Abualsaud et al. (42) found no significant difference in marginal fitness between printed and milled crowns and these groups were comparable. However, this study indicated that milled crowns were less precise than printed ones due to inaccuracy of milling machine burs. Based on Nakamura study, clinically acceptable range for marginal adaptation is less than 120 µm and for internal fitness is 30 µm-300 µm (66). Despite other articles, Li et al reported higher marginal and internal adaptation in stereo lithography (SLA) group compared to milling group due to limitation in milling machine. However, both were within acceptable range (44).

Refaie et al. (54) reported superior fracture resistance for printed zirconia crowns compared to milled crowns under cyclic loading. However, Kim et al. (53) found no significant difference in fracture resistance between the two techniques. Li et al. (61) also reported acceptable fracture resistance for both milled and printed zirconia crowns.

Overall, both 3D-printed and CAD/CAM milled zirconia crowns can be used clinically for dental restorations. (53,61) However, it is important to consider the fabrication technique and the intended use of the crown when selecting a material (67). For crowns that are subjected to high levels of stress, such as molar crowns, a milled zirconia crown may be a more suitable choice. For crowns that are subjected to lower levels of stress, such as anterior crowns, a 3D-printed zirconia crown may be a suitable choice (54, 67,68).

It is also important to note that the fracture resistance of zirconia crowns can be affected by a number of factors, including the design of the crown, the type of cement used, and the occlusion of the patient. Therefore, it is important to consider all of these factors when selecting a zirconia crown for a patient (53-54,61,67-68).

5. Conclusion

Based on the reviewed studies, 3D printing demonstrates superior axial fitness compared to subtractive manufacturing. While subtractive manufacturing generally exhibits higher marginal fitness, both techniques fall within acceptable clinical limits. A strong correlation exists between cement space and fitness, suggesting careful attention to this factor is crucial.

The layering process inherent to 3D printing can lead to inaccuracies in horizontal surfaces, whereas vertical surfaces display optimal accuracy. Conversely, bur turning limitations in subtractive manufacturing contribute to mismatches, particularly in specific areas.

Despite these differences, 3D printing offers acceptable fatigue resistance. However, the variability in methodologies, including tooth preparation, marginal discrepancy evaluation, sample size, finish lines, scanning techniques, restoration design, milling technology, and crown thickness, hinders direct comparisons between studies.

To definitively determine the most suitable additive system for ceramic restorations, further research is necessary to standardize these variables and conduct rigorous comparative evaluations.

Ethical Considerations

Compliance with ethical guidelines

Not applicated.

Funding

None.

Authors’contributions

Maryam Jahangiri: Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing-Original draft, Writing-review & editing.
Hedie Derakhshi: Conceptualization, Investigation, Resources, Software, Validation, Visualization, Writing-Original draft
Sayed Shojaedin Shayegh: Data curation, Project administration, Supervision

Conflict of Interests

The authors declare no conflict of interests.

Availability of data and material

Not applicable

Acknowledgments

None.

References

1. Guazzato M, Albakry M, Ringer SP, Swain MV. Strength, fracture toughness and microstructure of a selection of all-ceramic materials. Part II. Zirconia-based dental ceramics. Dent Mater. 2004;20(5):449-56.[DOI: 10.1016/j.dental.2003.05.002] [PMID]

2. Hannink R, Kelly P, Muddle B. Transformation Toughening in Zirconia-Containing Ceramics. Journal of the American Ceramic Society. 2000;83:461-87. [DOI:10.1111/j.1151-2916.2000.tb01221.x]

3. Piconi C, Maccauro G. Zirconia as a ceramic biomaterial. Biomaterials. 1999;20(1):1-25. [DOI: 10.1016/s0142-9612(98)00010-6] [PMID]

4. Teixeira EC, Piascik JR, Stoner BR, Thompson JY. Dynamic fatigue and strength characterization of three ceramic materials. J Mater Sci Mater Med. 2007;18(6):1219-24. [DOI: 10.1007/s10856-007-0131-4] [PMID]

5. Heintze SD, Rousson V. Survival of zirconia- and metal-supported fixed dental prostheses: a systematic review. Int J Prosthodont. 2010;23(6):493-502. [PMID]

6. Beuer F, Stimmelmayr M, Gernet W, Edelhoff D, Güth JF, Naumann M. Prospective study of zirconia-based restorations: 3-year clinical results. Quintessence Int. 2010;41(8):631-7. [PMID]

7. Beuer F, Stimmelmayr M, Gueth JF, Edelhoff D, Naumann M. In vitro performance of full-contour zirconia single crowns. Dent Mater. 2012;28(4):449-56. [DOI: 10.1016/j.dental.2011.11.024] [PMID]

8. Rinke S, Fischer C. Range of indications for translucent zirconia modifications: clinical and technical aspects. Quintessence Int. 2013;44(8):557-66. [DOI: 10.3290/j.qi.a29937] [PMID]

9. Strub JR, Rekow ED, Witkowski S. Computer-aided design and fabrication of dental restorations: current systems and future possibilities. J Am Dent Assoc. 2006;137(9):1289-96. [DOI: 10.14219/jada.archive.2006.0389] [PMID]

10. Ebert J, Ozkol E, Zeichner A, Uibel K, Weiss O, Koops U, et al. Direct inkjet printing of dental prostheses made of zirconia. J Dent Res. 2009;88(7):673-6. [DOI: 10.1177/0022034509339988] [PMID]

11. Wang H, Aboushelib MN, Feilzer AJ. Strength influencing variables on CAD/CAM zirconia frameworks. Dent Mater. 2008;24(5):633-8. [DOI: 10.1016/j.dental.2007.06.030] [PMID]

12. Huang H. Machining characteristics and surface integrity of yttria stabilized tetragonal zirconia in high speed deep griding. Materials Science and Engineering: A. 2003;345:155-63. [DOI:10.1016/S0921-5093(02)00466-5]

13. Abduo J, Lyons K, Bennamoun M. Trends in computer-aided manufacturing in prosthodontics: a review of the available streams. Int J Dent. 2014;2014:783948. [DOI: 10.1155/2014/783948] [PMID] [PMCID]

14. Barazanchi A, Li KC, Al-Amleh B, Lyons K, Waddell JN. Additive Technology: Update on Current Materials and Applications in Dentistry. J Prosthodont. 2017;26(2):156-63. [DOI: 10.1111/jopr.12510] [PMID]

15. Sun J, Zhang FQ. The application of rapid prototyping in prosthodontics. J Prosthodont. 2012;21(8):641-4. [DOI: 10.1111/j.1532-849X.2012.00888.x] [PMID]

16. ISO/ASTM 52900:2021; Standard Terminology for Additive Manufacturing—General Principles—Terminology. ASTM International: West Conshohocken, PA, USA, 2021. [Link]

17. Zeng L, Zhang Y, Liu Z, Wei B. Effects of repeated firing on the marginal accuracy of Co-Cr copings fabricated by selective laser melting. J Prosthet Dent. 2015;113(2):135-9. [DOI: 10.1016/j.prosdent.2014.09.004] [PMID]

18. Kim KB, Kim JH, Kim WC, Kim JH. Three-dimensional evaluation of gaps associated with fixed dental prostheses fabricated with new technologies. J Prosthet Dent. 2014;112(6):1432-6. [DOI: 10.1016/j.prosdent.2014.07.002] [PMID]

19. Hoang LN, Thompson GA, Cho SH, Berzins DW, Ahn KW. Die spacer thickness reproduction for central incisor crown fabrication with combined computer-aided design and 3D printing technology: an in vitro study. J Prosthet Dent. 2015;113(5):398-404. [DOI: 10.1016/j.prosdent.2014.11.004] [PMID]

20. Xu D, Xiang N, Wei B. The marginal fit of selective laser melting-fabricated metal crowns: an in vitro study. J Prosthet Dent. 2014;112(6):1437-40. [DOI: 10.1016/j.prosdent.2014.05.018] [PMID]

21. Wu J, Gao B, Tan H, Chen J, Tang CY, Tsui CP. A feasibility study on laser rapid forming of a complete titanium denture base plate. Lasers Med Sci. 2010;25(3):309-15. [DOI: 10.1007/s10103-008-0603-x] [PMID]

22. Williams RJ, Bibb R, Eggbeer D, Collis J. Use of CAD/CAM technology to fabricate a removable partial denture framework. J Prosthet Dent. 2006;96(2):96-9. [DOI: 10.1016/j.prosdent.2006.05.029] [PMID]

23. Chen G, Zeng X, Wang Z, Guan K, Peng C. Fabrication of Removable Partial Denture Framework by Selective Laser Melting. Advanced Materials Research. 2011;317-319:174-8. [DOI:10.4028/www.scientific.net/AMR.317-319.174]

24. Han J, Wang Y, Lü P. A preliminary report of designing removable partial denture frameworks using a specifically developed software package. Int J Prosthodont. 2010;23(4):370-5. [PMID]

25. Mangano F, Pozzi-Taubert S, Zecca PA, Luongo G, Sammons RL, Mangano C. Immediate restoration of fixed partial prostheses supported by one-piece narrow-diameter selective laser sintering implants: a 2-year prospective study in the posterior jaws of 16 patients. Implant Dent. 2013;22(4):388-93. [DOI: 10.1097/ID.0b013e31829afa9d] [PMID]

26. Alghazzawi TF. Advancements in CAD/CAM technology: Options for practical implementation. J Prosthodont Res. 2016;60(2):72-84. [DOI: 10.1016/j.jpor.2016.01.003] [PMID]

27. ISO 5725-1: Accuracy (trueness and precision) of measurement methods and results - Part 1: General principles and definitions., p.1 (1994). [Link]

28. Bosch G, Ender A, Mehl A. A 3-dimensional accuracy analysis of chairside CAD/CAM milling processes. J Prosthet Dent.

2014;112(6):1425-31. [DOI: 10.1016/j.prosdent.2014.05.012] [PMID]

29. Lee KB, Park CW, Kim KH, Kwon TY. Marginal and internal fit of all-ceramic crowns fabricated with two different CAD/CAM systems. Dent Mater J. 2008;27(3):422-6. [DOI: 10.4012/dmj.27.422] [PMID]

30. Contrepois M, Soenen A, Bartala M, Laviole O. Marginal adaptation of ceramic crowns: a systematic review. J Prosthet Dent. 2013;110(6):447-54.e10. [DOI: 10.1016/j.prosdent.2013.08.003] [PMID]

31. Kosyfaki P, del Pilar Pinilla Martín M, Strub JR. Relationship between crowns and the periodontium: a literature update. Quintessence Int. 2010;41(2):109-26. [PMID]

32. Kohorst P, Butzheinen LO, Dittmer MP, Heuer W, Borchers L, Stiesch M. Influence of preliminary damage on the load-bearing capacity of zirconia fixed dental prostheses. J Prosthodont. 2010;19(8):606-13. [DOI: 10.1111/j.1532-849X.2010.00640.x] [PMID]

33. Choi SH, Chan AMM. A virtual prototyping system for rapid product development. Computer-Aided Design. 2004;36:401-12. [DOI:10.1016/S0010-4485(03)00110-6]

34. Renne W, Ludlow M, Fryml J, Schurch Z, Mennito A, Kessler R, et al. Evaluation of the accuracy of 7 digital scanners: An in vitro analysis based on 3-dimensional comparisons. J Prosthet Dent. 2017;118(1):36-42. [DOI: 10.1016/j.prosdent.2016.09.024] [PMID]

35. Anadioti E, Aquilino SA, Gratton DG, Holloway JA, Denry IL, Thomas GW, et al. Internal fit of pressed and computer-aided design/computer-aided manufacturing ceramic crowns made from digital and conventional impressions. J Prosthet Dent. 2015;113(4):304-9. [DOI: 10.1016/j.prosdent.2014.09.015] [PMID]

36. Zhang Y, Mai Z, Barani A, Bush M, Lawn B. Fracture-resistant monolithic dental crowns. Dent Mater. 2016 Mar;32(3):442-9. [DOI: 10.1016/j.dental.2015.12.010] [PMID] [PMCID]

37. Hsu H-J, Lee S-Y, Jiang C-P, Lin R. A comparison of the marginal fit and mechanical properties of a zirconia dental crown using CAM and 3DSP. Rapid Prototyping Journal. 2019;ahead-of-print. [DOI:10.1108/RPJ-03-2018-0053]

38. Li R, Chen H, Wang Y, Sun Y. Performance of stereolithography and milling in fabricating monolithic zirconia crowns with different finish line designs. J Mech Behav Biomed Mater. 2021;115:104255. [DOI: 10.1016/j.jmbbm.2020.104255] [PMID]

39. Wang W, Sun J. Dimensional accuracy and clinical adaptation of ceramic crowns fabricated with the stereolithography technique. J Prosthet Dent. 2021;125(4):657-63. [DOI: 10.1016/j.prosdent.2020.02.032] [PMID]

40. Wang W, Yu H, Liu Y, Jiang X, Gao B. Trueness analysis of zirconia crowns fabricated with 3-dimensional printing. J Prosthet Dent. 2019;121(2):285-91. [DOI: 10.1016/j.prosdent.2018.04.012] [PMID]

41. Refaie A, Fouda A, Bourauel C, Singer L. Marginal gap and internal fit of 3D printed versus milled monolithic zirconia crowns. BMC Oral Health. 2023;23(1):448. [DOI: 10.1186/s12903-023-03184-8] [PMID] [PMCID]

42. Abualsaud R, Alalawi H. Fit, Precision, and Trueness of 3D-Printed Zirconia Crowns Compared to Milled Counterparts. Dent J (Basel). 2022;10(11). [DOI: 10.3390/dj10110215] [PMID] [PMCID]

43. Lerner H, Nagy K, Pranno N, Zarone F, Admakin O, Mangano F. Trueness and precision of 3D-printed versus milled monolithic zirconia crowns: An in vitro study. J Dent. 2021;113:103792. [DOI: 10.1016/j.jdent.2021.103792] [PMID]

44. Li B, Jiang Q, Meng D. Evaluation of the trueness and adaptation of zirconia crowns fabricated with stereolithography. Dent Mater J. 2023;42(3):441-8. [DOI: 10.4012/dmj.2022-146] [PMID]

45. Marouki C, Shamon A, Svanborg P. Evaluation of fit and accuracy of single crowns fabricated from self-glazed zirconia compared with milled zirconia. J Prosthet Dent. 2023. [DOI: 10.1016/j.prosdent.2023.02.016] [PMID]

46. Aggag M, Abd Elkader S, Bakry S. MARGINAL AND INTERNAL FIT EVALUATION OF CAD/CAM ZIRCONIA CROWNS FABRICATED BY STONE DIES VERSUS 3D PRINTED DIES. Alexandria Dental Journal. 2024;49(2):137-142. [DOI:10.21608/adjalexu.2023.177753.1330]

47. Cameron AB, Choi JJE, Ip A, Lyons N, Yaparathna N, Dehaghani AE, et al. Assessment of the trueness of additively manufactured mol3% zirconia crowns at different printing orientations with an industrial and desktop 3D printer compared to subtractive manufacturing. Journal of dentistry. 2024;144:104942. [DOI: 10.1016/j.jdent.2024.104942] [PMID]

48. Kalman L, Tribst JPM. Quality Assessment and Comparison of 3D-Printed and Milled Zirconia Anterior Crowns and Veneers: In Vitro Pilot Study. European Journal of General Dentistry. 2024. [DOI:10.1055/s-0044-1782183]

49. Revilla-León M, Methani MM, Morton D, Zandinejad A. Internal and marginal discrepancies associated with stereolithography (SLA) additively manufactured zirconia crowns. J Prosthet Dent. 2020;124(6):730-7. [DOI: 10.1016/j.prosdent.2019.09.018] [PMID]

50. Xiao P, Zheng Z, Zhang Y, Zeng Y, Yan W. Accuracy and adaptation of one-piece endodontic crowns fabricated through 3D printing and milling. The Journal of Prosthetic Dentistry. 2024;132(2):422-433. [DOI: 10.1016/j.prosdent.2024.05.011] [PMID]

51. Thomas AA, Daniel AY, Gandhi N, Roy N, Varghese KG, Wadhwa S, et al. Surface trueness and precision of interim restorations fabricated by digital light processing and CAD-CAM milling systems. The Journal of prosthetic dentistry. 2023. [DOI: 10.1016/j.prosdent.2023.07.006] [PMID]

52. Kang SY, Park JH, Kim JH, Kim WC. Accuracy of provisional crowns made using stereolithography apparatus and subtractive technique. J Adv Prosthodont. 2018;10(5):354-60. [DOI: 10.4047/jap.2018.10.5.354] [PMID] [PMID]

53. Kim YK, Han JS, Yoon HI. Evaluation of intaglio surface trueness, wear, and fracture resistance of zirconia crown under simulated mastication: a comparative analysis between subtractive and additive manufacturing. J Adv Prosthodont. 2022;14(2):122-32.

[DOI: 10.4047/jap.2022.14.2.122] [PMID] [PMCID]

54. Refaie A, Bourauel C, Fouda AM, Keilig L, Singer L. The effect of cyclic loading on the fracture resistance of 3D-printed and CAD/CAM milled zirconia crowns—an in vitro study. Clinical Oral Investigations. 2023;27(10):6125-33. [DOI: 10.1007/s00784-023-05229-2] [PMID] [PMCID]

55. Rues S, Zehender N, Zenthöfer A, Bömicke W, Herpel C, Ilani A, et al. Fit of anterior restorations made of 3D-printed and milled zirconia: An in-vitro study. Journal of Dentistry. 2023;130:104415. [DOI: 10.1016/j.jdent.2023.104415] [PMID]

56. Camargo B, Willems E, Jacobs W, Van Landuyt K, Peumans M, Zhang F, et al. 3D printing and milling accuracy influence full-contour zirconia crown adaptation. Dental Materials. 2022;38(12):1963-76. [DOI: 10.1016/j.dental.2022.11.002] [PMID]

57. Ioannidis A, Park J-M, Hüsler J, Bomze D, Mühlemann S, Özcan M. An in vitro comparison of the marginal and internal adaptation of ultrathin occlusal veneers made of 3D-printed zirconia, milled zirconia, and heat-pressed lithium disilicate. The Journal of Prosthetic Dentistry. 2022;128(4):709-15. [DOI: 10.1016/j.prosdent.2020.09.053] [PMID]

58. Lim YA, Kim JM, Choi Y, Park S. Evaluation of Fitness and Accuracy of Milled and Three-Dimensionally Printed Inlays. European Journal of Dentistry. 2023;17(04):1029-36. [DOI: 10.1055/s-0042-1758796] [PMID] [PMCID]

59. Abad-Coronel C, Bravo M, Tello S, Cornejo E, Paredes Y, Paltan CA, et al. Fracture Resistance Comparative Analysis of Milled-Derived vs. 3D-Printed CAD/CAM Materials for Single-Unit Restorations. Polymers. 2023;15(18):3773. [DOI: 10.3390/polym15183773] [PMID] [PMCID]

60. Zhu H, Zhou Y, Jiang J, Wang Y, He F. Accuracy and margin quality of advanced 3D-printed monolithic zirconia crowns. J Prosthet Dent. 2023. [DOI: 10.1016/j.prosdent.2023.07.004] [PMID]

61. Li R, Wang Y, Hu M, Wang Y, Xv Y, Liu Y, et al. Strength and adaptation of stereolithography-fabricated zirconia dental crowns: an in vitro study. Int J Prosthodont. 2019;32(5):439-43. [DOI: 10.11607/ijp.6262] [PMID]

62. Abduo J, Ho G, Centorame A, Chohan S, Park C, Abdouni R, et al. Marginal Accuracy of Monolithic and Veneered Zirconia Crowns Fabricated by Conventional and Digital Workflows. J Prosthodont. 2023;32(8):706-13. [DOI: 10.1111/jopr.13618] [PMID]

63. Liberati A, Altman DG, Tetzlaff J, Mulrow C, Gøtzsche PC, Ioannidis JP, et al. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. J Clin Epidemiol. 2009;62(10):e1-34. [DOI: 10.1016/j.jclinepi.2009.06.006] [PMID]

64. Vandenbroucke B, Kruth J-P. Selective laser melting of biocompatible metals for rapid manufacturing of medical parts. Rapid Prototyping Journal. 2007;13:196-203. [DOI:10.1108/13552540710776142]

65. Silva NR, Witek L, Coelho PG, Thompson VP, Rekow ED, Smay J. Additive CAD/CAM process for dental prostheses. J Prosthodont. 2011;20(2):93-6. [DOI: 10.1111/j.1532-849X.2010.00623.x] [PMID]

66. Nakamura K, Mouhat M, Nergård JM, Lægreid SJ, Kanno T, Milleding P, et al. Effect of cements on fracture resistance of monolithic zirconia crowns. Acta Biomater Odontol Scand. 2016;2(1):12-9. [DOI: 10.3109/23337931.2015.1129908] [PMID] [PMCID]

67. Othman A, Sandmair M, Alevizakos V, von See C. The fracture resistance of 3D-printed versus milled provisional crowns: An in vitro study. Plos one. 2023 Sep 1;18(9):e0285760. [DOI: 10.1371/journal.pone.0285760]

68. Alghauli M, Alqutaibi AY, Wille S, Kern M. 3D-printed versus conventionally milled zirconia for dental clinical applications: Trueness, precision, accuracy, biological and esthetic aspects. Journal of Dentistry. 2024 Mar 11:104925. [DOI: 10.1016/j.jdent.2024.104925] [PMID]